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TECHNICAL SCIENCE

A 10 GHz Monolithic Filter Based on Stripline Resonators with a Split Conductor

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Abstract—The monolithic design of a compact bandpass filter X-band is made on the technology of multilayered printed circuit boards. Quarter-wave stripline resonators of the filter have two conductors divided by a layer of prepreg having low parameters that bond together the design. This eliminates the influence of the prepreg on the characteristics of the devices, ensuring good repeatability of filters in mass production. To increase the high-frequency stopband of the filter, one of the conductors of each resonator is cut in half by a transverse slit. The constructive sizes of the device were obtained by parametric synthesis using the electrodynamic analysis of its 3D model. The experimental data of the five-order filter are in good agreement with the electromagnetic simulation of filter of the 3D model. The experimental device has a central frequency of the passband of 10 GHz and a fractional bandwidth of 5.7%, and its dimensions and weight are 18.0 × 5.4 × 2.1 mm^3 and 0.5 g. The important advantage of the developed design is the possibility of its installation on the board using the surface mounting method.

Keywords: bandpass filter, frequency response, return loss, insertion loss, impedance, layered structure

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It is well known that the most important devices of modern radio systems for transmitting, receiving, and processing signals are bandpass filters, on which not only the quality of radio equipment depends, but also its dimensions and even price. Therefore, the development of new miniature filter designs with high frequency-selective properties, manufacturability, and low cost for mass production is an important and urgent task. To solve this problem, designs based on stripline multiconductor resonant structures [1, 2], which have not only a record miniature size among electrodynamic resonators, but also a relatively high unloaded quality factor, are currently being studied actively. At present, a promising direction associated with the use of hybrid technology for creating multilayer microwave integrated circuits based on ceramics with low annealing temperatures (Low Temperature Cofired Ceramics (LTCC)) has become widespread [3–6], as has the original technology of integrating waveguides into the substrate (Substrate Integrated Waveguide (SIW)) [7–9]. Moreover, among all the known approaches used for manufacturing planar microwave filters, the technology of multilayer printed circuit boards (Printed Circuit Board (PCB)) [10–13], which has the ability to organize mass production of monolithic structures [14], stands out.

In the PCB technology to connect dielectric plates with patterns of strip conductors on the surfaces by pressing, a special material is used, prepreg, the dielectric losses of which are higher than the dielectric losses of the main layers. This is a disadvantage of the technology, as it reduces the unloaded quality factor of the resonators, thereby worsening the characteristics of the filters. The second drawback is due to the fact that, during the pressing of the layered structure, the thickness of the prepreg changes uncontrollably in area in accordance with the pattern and thickness of the strip conductors, leading to a change not only in the resonant frequencies, but also in the value of the interaction between the resonators. In the decimeter and meter ranges, changes in the thickness of the prepreg have virtually no effect on the characteristics of the filters [14, 15], however, at frequencies above 4 GHz, the resonator conductors are greatly shortened, and the influence of the prepreg becomes critical, unacceptably reducing the repeatability of devices

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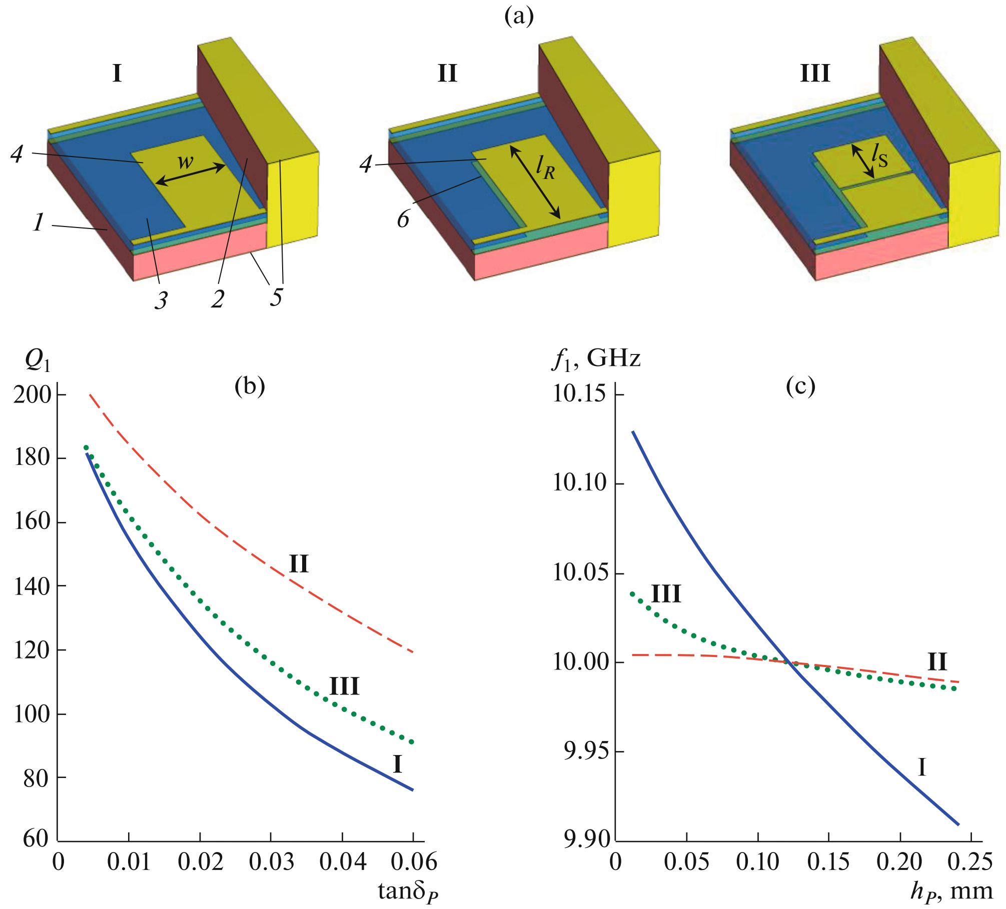

Fig. 1. (a) Three designs of monolithic quarter-wave strip resonators, (b) the dependence of the unloaded quality factor of their resonances on the dielectric loss tangent of the prepreg, and (c) the dependence of the resonant frequencies on the thickness of the prepreg.

in the series. This paper discusses a new approach to designing monolithic stripline filters, which makes it possible largely to neutralize the influence of the prepreg, even in the centimeter wavelength range.

DESIGNS OF MONOLITHIC QUARTER-WAVE STRIPE RESONATORS

Consider a regular quarter-wave strip resonator **I** (Fig. 1a), made using PCB technology by pressing two dielectric plates (*1* and *2*), between which there is a prepreg bonding layer (*3*). The copper conductor of the resonator (*4*) is located between the top plate (*2*) and the prepreg layer (*3*). The role of the housing-screen is performed by external metallization of the surfaces of dielectric plates (*5*). Obviously, in such a design the parameters of the prepreg (its thickness h_P and dielectric loss tangent $\tan\delta_P$) will have a direct impact on the characteristics of the resonator, in particular, on its own quality factor and resonant frequency. However, as is known [16], the influence of the prepreg is significantly weakened if the resonator conductor is split by placing the prepreg between metal layers *4* and *6* (design **II,** Fig. 1a), connected to the screen by adjacent ends only on one side.

In this design, at the quarter-wave resonance frequency, the potential difference between opposite points on the upper and lower conductor is zero, so the influence of the prepreg parameters on the characteristics of the resonator is greatly weakened. But it is important to note that near the main resonance of the structure **II** (Fig. 1a), observed at frequency f_1, there is a parasitic resonance at higher frequency f_2, corresponding to oscillations in a quarter-wave resonator formed by a prepreg layer and two co-directional conductors *4* and *6* on its surfaces. The free ends of these conductors at the frequency f_2 have opposite potentials, and microwave currents are directed towards each other [17]. As a result, the high-frequency stopband of a filter formed on such resonators narrows, and to expand it, obviously, it is necessary to increase significantly the frequency f_2 without changing fre-

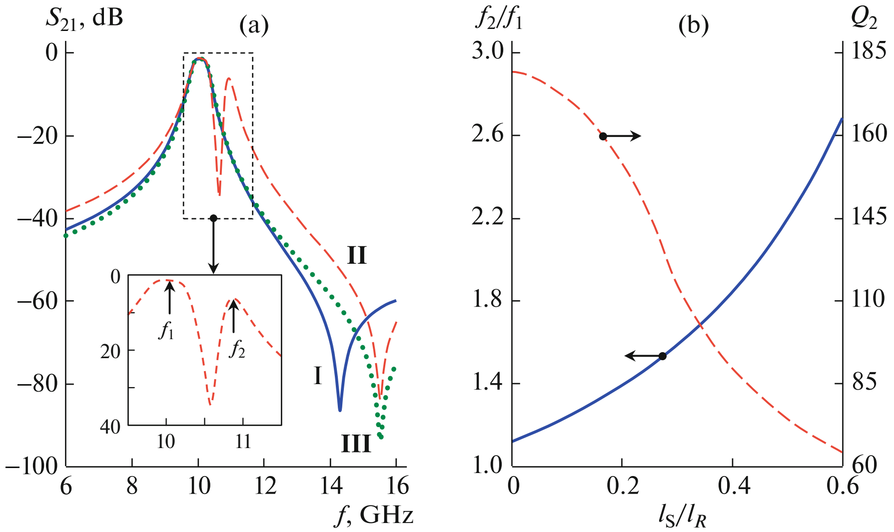

Fig. 2. (a) Frequency response of second-order filters synthesized on resonators of various designs. (b) Dependence of the quality factor of parasitic resonance Q_2 and ratios of frequency of parasitic f_2 and main f_1 resonances from the relative position of the slit l_S/l_R on the upper conductor of the resonator structure **III** (see Fig. 1a).

quency f_1. This can be accomplished by making a transverse slit on the upper conductor of a two-conductor resonator at the distance l_S from the free end (see design **III** in Fig. 1a).

The above is confirmed by the results of studies (Figs. 1b, 1c) carried out using electrodynamic analysis of 3D models of resonators in the CST Studio Suite software package. For an objective comparison, the design parameters of the resonator models were the same; in particular, the width of the strip conductors of the resonators $w = 2$ mm. In this case, the characteristics of real metallized dielectric plates and prepreg were used. Resonator plates made of RO4350B material with relative dielectric constant $\varepsilon_R = 3.66$ and dielectric loss tangent $\tan\delta_R = 0.0037$ had a thickness of 0.762 mm and 1.44 mm. Prepreg made of RO4450F material with the relative dielectric constant $\varepsilon_P = 3.52$ and $\tan\delta_P = 0.0041$ had a layer thickness $h_P = 0.122$ mm. The length of strip conductor l_R of the resonators was tuned to the same frequency of the first (quarter-wave) oscillation mode $f_1 = 10$ GHz.

As would be expected, for a fixed prepreg thickness $h_P = 0.122$ mm, the unloaded quality factor of all resonators with increasing $\tan\delta_P$ in the range of 0.004–0.050 decreases monotonically (Fig. 1b). Moreover, for the first design there is a decrease of 2.4 times; for the second, by 1.7; and for the third, exactly by two times in the case when a 0.1 mm gap divides the upper conductor in half. Figure 1c shows the behavior of the resonant frequency of the three structures under study, plotted when changing the initial thickness of the prepreg $h_P = 0.122$ mm within 0.01–0.24 mm, but at a fixed value $\tan\delta_P = 0.0041$. In this case, the largest changes in the resonant frequency are observed only in the first design: with a decrease h_P up in frequency by ~1.3%, and with increasing h_P on ~0.9% down in frequency. Note that the intrinsic quality factor Q_1 resonance design **II** (see Fig. 1a) throughout the entire range of changes h_P remains almost constant, and designs **I** and **III** with reduction h_P increase by ~3%, and with increasing h_P decrease by ~0.5%.

CHARACTERISTICS OF TWO-LINK FILTERS ON MONOLITHIC RESONATORS

To compare the characteristics of stopbands of filters built on the studied resonators, second-order devices were designed by parametric synthesis of 3D models of the simplest two-link structures in the CST Studio Suite software package. The frequency response (FR) of filters, demonstrating the frequency dependences of transmission losses $S_{21}(f)$, are presented in Fig. 2a. The synthesized filters have the same passband center frequency $f_1 = 10$ GHz and its relative width $\Delta f/f_1 = 5\%$, measured at –3dB of the minimum loss level. The input and output of each device are conductively connected to ports with a characteristic impedance of 50 Ω. The filters were adjusted by selecting the length of the strip conductors, the gaps between them, and the value of the conductive coupling of the resonators with the ports so that the maximum reflected microwave power in the passband was at a level of –14 dB.

Figure 2a clearly shows that the filter based on resonators of the design has the best characteristics in the stop bands **III** (see Fig. 1a), in which the gap divides the upper strip conductors in half, and the worst, on the resonators of structure **II**, due to parasitic resonance located near the passband at frequency f_2, the nature of which was explained above. In Fig. 2b the solid line shows the dependence of the parasitic frequency ratio f_2 and main f_1 resonances from the relative position of the slit l_S/l_R on the upper conductor of the resonator structure **III** (see Fig. 1a). Moving the slot from the free end of the strip conductor to the end closed to the screen leads to a rapid increase in the parasitic resonance frequency f_2, and the frequency of the main resonance $f_{1;}$ however, it remains practically unchanged. As a result, a significant expansion of the high-frequency filter stopband occurs. Note that with increasing l_S/l_R there is a strong drop in the unloaded quality factor of the parasitic resonance Q_2 (dashed line in Fig. 2b), which also improves the characteristics of the stopband strip. In the studied interval of change l_S/l_R, quality factor Q_2 decreases three times, but the quality factor Q_1, however, remains almost unchanged.

The fact of decreasing quality factor Q_2 can be explained by the effect of damping oscillations in the resonator when a line segment with losses is connected to it. This effect was studied in detail in [18] on microstrip resonators, in which a damping line segment was created by exposing a thin adhesive sublayer of chromium by removing copper in a small section along the length of the strip conductor located near the antinode of the electric field. It was shown that, with an increase in the length of this section, the quality factor of the resonance decreases several times, and the nature of the change in the quality factor established in [18] on the length of the damping line segment is in good agreement with the dependence $Q_2(l_S/l_R)$ (see Fig. 2b). In our study, a section of the damping line in the resonator of the structure **III** (see Fig. 1a), limited by a strip conductor of length l_S and its width w, is connected to the quarter-wave resonator by the transverse slot capacitance, the value of which in the model under consideration is ~1.6 pF. Obviously, with an increase l_S the length of the damping section increases proportionally and at the same time its capacitive coupling with the resonator increases, due to the rapid increase in the resonant frequency f_2 (see Fig. 2b). As a result, the vibration damping in the resonator increases, and therefore, its quality factor decreases.

STUDY OF A PROTO SAMPLE OF A FIFTH ORDER FILTER

To test the performance of a monolithic device experimentally, the design of a fifth-order filter built on the studied resonator **III** was chosen, the electrodynamic 3D model of which is presented in Fig. 3a. The same materials were used as dielectric plates and prepreg in the filter model, the characteristics and the layer thicknesses of which were given above. The width of the resonator conductors is the same $w = 2$ mm, as well as the width of the slots of 0.1 mm and their relative location $l_S/l_R = 0.24$.

By parametric synthesis in the CST Studio Suite software package, the design parameters of the model connected to ports with a characteristic impedance of 50 Ω were determined, at a given center frequency of the passband $f_0 = 10$ GHz and its width $\Delta f = 570$ MHz, measured at –3 dB. In this case, the maximum reflected microwave power in the passband should not exceed the level of –20 dB. As a result of the synthesis, the length of the strip conductors of the outer resonators was 3.46 mm, the following ones were 3.31 mm, and the conductor of the central resonator was 3.29 mm. The gap size between the conductors of the outer pairs of resonators was 0.85 mm, and between the conductors of the remaining internal resonators, it was 1.25 mm. The obtained design parameters were used to manufacture a series of prototypes of monolithic filters using multilayer printed circuit board technology; a photograph of one of them is shown in Fig. 3b. Filter sizes 18.0 × 5.4 × 2.1 mm or $0.6\lambda_0 \times 0.18\lambda_0 \times 0.07\lambda_0$ (λ_0 is the wavelength in a vacuum at the center frequency of the passband), and the device weighs only 0.5 g.

Figure 3c shows the calculated frequency dependences of direct losses $S_{21}(f)$ (solid line) and reflection losses $S_{11}(f)$ (dashed line) of the filter under study; the dots show the measurement results of the manufactured prototype. A good agreement between the calculated and measured characteristics can be seen. The measured center frequency of the passband was $f_0 = 9.98$ GHz, and the relative bandwidth was measured at –3 dB level, $\Delta f/f_0 = 5.7\%$. The high-frequency stopband width at –40 dB extends to almost 14 GHz. The minimum attenuation of microwave power in the filter passband was 4.2 dB, and the level of reflections in the passband did not exceed –20 dB.

CONCLUSIONS

Thus, the monolithic design of a miniature strip bandpass filter in the centimeter wavelength range has been developed, intended for mass production using multilayer printed circuit board technology. A special feature of the design is quarter-wave resonators with prepreg-split two-layer strip conductors, in which one of the conductors is cut by a transverse slit. It is shown that the unloaded quality factor of a quarter-wave strip resonator with a two-layer conductor is significantly higher than a traditional resonator with a single-layer conductor, and a transverse slot in one of the conductors significantly expands the high-frequency stop band of the device. On a multilayer printed circuit board with an area of 460 × 610 mm there were 480 pieces of filters, of which 390 pieces had a deviation of the central frequency from 10 GHz that did not exceed ±25 MHz. The bandwidth did not go beyond the interval 570 ± 5 MHz, and the minimum loss in

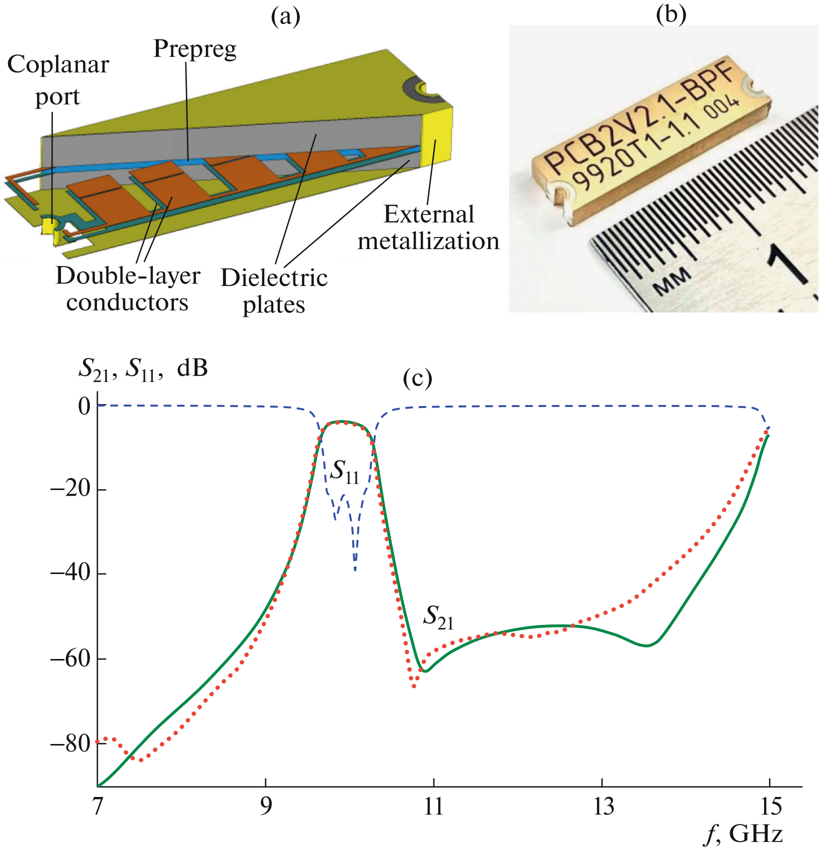

Fig. 3. (a) 3D model of a fifth-order monolithic filter, (b) photograph of the prototype, and (c) frequency response of the device; lines are calculations, and points are the experiment.

the passband varied within 4.2 ± 0.2 dB. For the remaining filters, located mainly at the edges of the printed circuit board, the deviations were approximately twice as large.

The low cost of the studied filters in mass production, as well as the high repeatability of characteristics even in the centimeter wavelength range, confirmed by a good agreement between the theoretical and measured frequency responses, proves the promise of using the developed design in radio engineering systems.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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